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Bayesian edge detector for SAR imagery using discontinuity-adaptive Markov random field modeling

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Abstract Synthetic aperture radar (SAR) image is severely affected by multiplicative speckle noise, which greatly complicates the edge detection. In this paper, by incorporating the discontinuity-adaptive Markov random field (DAMRF) and maximum a posteriori (MAP) estimation criterion into edge detection, a Bayesian edge detector for SAR imagery is accordingly developed. In the proposed detector, the DAMRF is used as the a priori distribution of the local mean reflectivity, and a maximum a posteriori estimation of it is thus obtained by maximizing the posteriori energy using gradient–descent method. Four normalized ratios constructed in different directions are computed, based on which two edge strength maps (ESMs) are formed. The final edge detection result is achieved by fusing the results of two thresholded ESMs. The experimental results with synthetic and real SAR images show that the proposed detector could efficiently detect edges in SAR images, and achieve better performance than two popular detectors in terms of Pratt's figure of merit and visual evaluation in most cases.

1. Introduction

Synthetic aperture radar (SAR) has the ability to image the areas of interest in all day and all weather conditions, and high-resolution images produced by it can be used for mapping, surface surveillance, earth source monitoring, automatic target recognition (ATR), and so on. Edge detection is a fundamental issue for many SAR image applications ranging from segmentation,[1] oil spills detection,[2] to ATR.[3] It concerns the identification of transitions indicating the boundaries between regions with uniform reflectivity in SAR image.[4]

Unlike optical imaging sensors, SAR utilizes the coherent imaging principle to yield images, and thus SAR images will be inevitably affected by the coherence speckle noise.[5] The multiplicative nature of speckle noise, in the sense that the noise level increases with the magnitude of radar backscattering, makes edge detection in SAR image very different from that in the images corrupted by additive noise.[6] In this case, the traditional gradient-based edge detectors such as Sobel edge filter have been proved to be ineffective in detecting edges in SAR image.[7] On the other hand, SAR image with low look usually carries heavy speckle noise, making the signal-to-noise ratio (SNR) very low, which also brings about great difficulty in edge detection.

To deal with the problem of correlated speckle noise existing in SAR image, several edge detectors designed specifically

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for SAR images have been proposed. These detectors can be roughly divided into two categories, known as ratio-based detectors and multiscale detectors. Representative ratio-based detectors, also called statistical detectors, include ratio of averages (ROA) detector,[8] likelihood ratio (LR) detector[9] and ratio of exponentially weighted averages (ROEWA) detector.[10] These detectors first estimate the local mean reflectivity, and then, combine the ratios of the estimated local mean reflectivity to form the edge strength map (ESM). Generally, the local maxima or minima in the ESM possibly indicate the presence of edges. Unlike the ratio-based detectors relying on the statistical properties of the SAR signals, multiscale detectors[11–13] utilize the fact that multiscale analysis has the useful property of space and scale localization, so it provides great promise for detecting image feature such as discontinuities at different scales. For example, Alonso et al.[12] proposed a multiscale edge enhancement algorithm that is divided into two steps: edge enhancement and decision, utilizing the fact that speckle noise behaves differently in different scales while the discontinuities could persist over scales. Besides the two kinds of detectors mentioned above, Tourneret et al.[14] proposed a Bayesian off-line edge detection algorithm, wherein the MMSE and maximum a posteriori (MAP) estimators are employed to estimate the edge positions in SAR image. This edge detection algorithm shows superiority to the ROEWA detector, but presents a high computational load due to the implementation of Markov chain Monte Carlo.

Markov random field (MRF) is a promising image analysis tool.[15] It characterizes the contextual or spatial information of an image via the definition of the prior potential functions, and has been applied to various image processing areas such as image restoration and segmentation, texture analysis and despeckling. However, to our best knowledge no application of MRF has been provided for edge detection in SAR image. Hence, in this paper, we propose a Bayesian technique in conjunction with MRF for edge detection in SAR image. The main contribution of this paper is to estimate the local mean reflectivity by maximizing their a posteriori distribution in the Bayesian framework, where in the discontinuity-adaptive (DA) MRF model[16] regularizing ill-posed problems is adopted as the prior distribution.

The paper is organized as follows. In Section 2, we describe the signal model and statistical property of SAR image. The definition of DA MRF is given in Section 3. The proposed edge detection algorithm for SAR images is presented in Section 4. In Section 5, extensive experiments are shown to verify the efficiency of the proposed detector and conclusions are provided in Section 6.

2. Signal model of SAR image

It is well-known that the radar echo signal received by SAR is the coherent sum of the reflected signals with distributed objects. The complex envelope of the received signal from each resolution cell is the summation of N scattering echoes in that cell with different amplitudes and phases, resulting from the interaction of electromagnetic waves backscattered by N different scatterers[17]:

$$Z(x,y) = \sum_{i=1}^{N} a_i e^{j\varphi_i} \tag{1}$$

where a_i and φ_i are the amplitude and phase of the ith scatterer, respectively, and assumed independent from each other; x and y are the coordinates of a SAR image. a_i governs the strength and angular distribution of the radiation, and φ_i depends on the position of the ith scatterer in the resolution cell, with respect to the coordinate x. If N is large, according to the central limit theorem, Z can be modeled as a complex random variable with independently and identically distributed real and imaginary components, following the zero-mean circular Gaussian distribution, i.e.,

$$p(Z) = \frac{1}{2\pi\sigma} e^{-|Z|^2/2\sigma} \qquad (Z \geqslant 0) \tag{2}$$

where σ stands for the RCS of the distributed object, the observed signals are the intensity image $I(x, y) = |Z(x, y)|^2$ or the amplitude image $A(x, y) = |Z(x, y)|$. In this study, we only consider the intensity SAR images. There is no difficulty to obtain the probability density function (pdf) of Z given in Eq. (2)

$$p(I) = \frac{1}{\sigma} e^{-I/\sigma} \qquad (I \geqslant 0) \tag{3}$$

It is apparent that the amplitude of Z is dependent not only on the reflection coefficients of the distributed objects but also on the distribution of the scattering centers over the distributed objects. Different positions of scattering centers result in different phases of these elements. For a certain ground object with constant reflection coefficient, the total backscattering signals are mainly contributed by the phases. In general, the random walk process is proper to describe the randomly distributed scatterers, assuming the phases of scatterers are uniformly distributed. Consequently, the observed signals can be seen as the determined radar cross section (RCS) of the ground object which is modulated by a random noise process. This random noise process is referred to as the so-called speckle noise. Assuming the speckle is fully developed and no scatterer is dominant, the observed intensity signal I can be expressed as the product of two independent signal components

$$I = \sigma n \tag{4}$$

and where n stands for the speckle noise. It is clearly that the distribution of n is the same as that of I, i.e., negative exponential distribution with mean value equal to one. To reduce the variance of speckle noise, L independent images are averaged. The resultant observed signals can be written as

$$I = \frac{1}{L} \sum_{l=1}^{L} I_l \tag{5}$$

Given Eqs. (2) and (5), we can obtain the pdf of I

$$p(I) = \frac{L^L}{\Gamma(L)} \frac{I^{L-1}}{\sigma} e^{-\frac{LI}{\sigma}} \qquad (I \geqslant 0) \tag{6}$$

where $\Gamma(L)$ is the Gamma function and L is called the number of looks.

3. DAMRF

Let $S = \{(x,y) | 1 \leqslant x, y \leqslant N\}$ denote a rectangular lattice for a 2D image with the size of $N \times N$, and $F = \{f_s | s \in S\}$ a family of random variables defined on S. F is called a Markov random field if the following two conditions are satisfied: (1) positivity